

Design and Fabrication of a Direct Natural Convection Solar Dryer for *Tapioca*

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Abstract

Based on preliminary investigations under controlled conditions of drying experiments, a direct natural convection solar dryer was designed and fabricated to dry *tapioca* in the rural area. This paper describes the design considerations followed and presents the results of MS excel computed results of the design parameters. A minimum of 7.56 m² solar collector area is required to dry a batch of 100 kg *tapioca* in 20 hours (two days drying period). The initial and final moisture content considered were 79 % and 10 % wet basis, respectively. The average ambient conditions are 32°C air temperatures and 74 % relative humidity with daily global solar radiation incident on horizontal surface of 13 MJ/m²/day. The weather conditions considered are of Warri (lat. 5°30', long. 5°41'), Nigeria. A prototype of the dryer so designed was fabricated with minimum collector area of 1.08 m². This prototype dryer will be used in experimental drying tests under various loading conditions.

Keywords

Solar dryer; *Tapioca*; Warri-Nigeria.

Introduction

Open-air and uncontrolled sun drying is still the most common method used to preserve and process agricultural products in most tropical and subtropical countries. However, being unprotected from rain, wind-borne dirt and dust, infestation by insects, rodents and other animals, products may be seriously degraded to the extent that sometimes become market valueless and inedible and the resulted loss of food quality in the dried products may have adverse economic effects on domestics and international markets. Some of the problems associated with open-air sun drying can be solved through the use of a solar dryer, which comprises of collector, a drying chamber and sometimes a chimney [1]. The conditions in tropical countries make the use of solar energy for drying food practically attractive and environmentally friendly. Dryers have been developed and used to dry agricultural products in order to improve market value and shelf life [2]. Most of these either use an expensive source of energy such as electricity [3] or a combination of solar energy and some other form of energy [4]. Most projects of this nature have not been adopted by the small farmers, either because the final design and data collection procedures are frequently inappropriate or the cost has remained unaffordable and the subsequent transfer of the technology from the researcher to the end user has been anything but ineffective [5].

Cassava, *Manihot esculenta* is a perennial woody shrub with an edible root, which grows in tropical and subtropical areas of the world. In 1999, Nigeria produced 33 million tonnes making it the world's largest producer and 15 [%] of the Nigeria produce is from Delta state [6]. Cassava is a very versatile commodity with numerous uses and by products. *Tapioca* that is very rough to touch is a by product of cassava and the consumption of *tapioca* is among the *Urhobos*, *Benins*, *Ijaws* and *Isokos*. It can be consumed without any additives or it can be consumed with a variety of additives such as sugar, groundnut, fish, meat, stew and pepper soup (called *Ifoniya-Ibadere* among the *Urhobos*). The processing of *tapioca* from cassava after harvesting is shown in Figure 1.

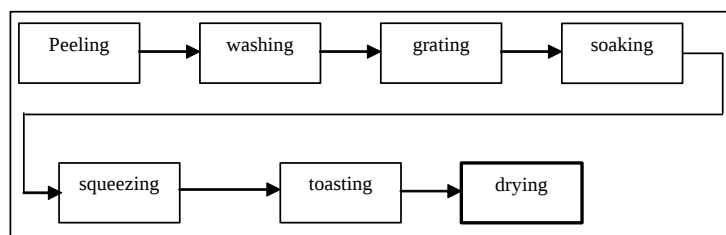


Figure 1. Tapioca processing sequence

Drying is the last stage in the processing of *tapioca* from cassava and is the most challenging because it makes the commodity to have a good/bad market value and also it serves as a preservation measure. The drying process is normally done locally by uncontrolled open-air sun drying on roofs, which is time consuming and unproductive and may cause spoilage of the commodity if eventually rain falls. It is, therefore, envisaged that the design of a simple solar dryer could contribute greatly in solving this problem.

Solar dryers may be classified according to the mode of air flow as natural convection and forced convection dryers. Natural convection dryers do not require a fan to blow the air through the dryer. Solar drying may also be classified into direct, indirect and mixed-modes. In direct solar dryers the air heater contains the materials and solar energy passes through a transparent cover and is absorbed by the materials. Essentially, the heat required for drying is provided by radiation to the upper layers and subsequent conduction into the material bed. In indirect dryers, solar energy is collected in a separate solar collector (air heater) and the heated air then passes through the material bed, while in the mixed-mode type of dryer, the heated air from a separate solar collector is passed through a material bed and at the same time, the drying cabinet or chamber absorbs solar energy directly through the transparent walls or roof.

Therefore, research efforts will be focused on designing and fabricating a simple direct natural convection dryer for Warri climatic zone. Since the rural or remote areas of Nigeria are not connected to the national electric grid and remote areas of Nigeria facing energy crisis, especially Niger Delta states. The use of solar technology has often been suggested for the dried fruit industry both to reduce energy costs and economically speed up drying, which would be beneficial to final quality [3, 7], dried grapes, okra, tomato and onion using solar energy. They concluded that drying time reduced significantly resulting in a higher product quality in terms of colour and reconstitution properties. They also believe that as compared to oil or gas heated dryers, solar drying facilities are economical for small holders, especially under favourable meteorological conditions.

Warri is a city in Delta state, Nigeria situated in latitude and longitude of $5^{\circ}30'$ and $5^{\circ}41'$, respectively with a mean air speed of 3.61 m/s. The measured monthly mean daily values maximum temperature, global radiation on horizontal surface and relative humidity of Warri in Delta State were collected from the archives of the Nigerian Meteorological Agency, Oshodi, Lagos State as shown in Table 1.

Table 1. Average Warri Meteorological Data

Month	Monthly Mean Temperature, t_d [°C]	Monthly mean daily global radiation on horizontal surface, I_h [MJ/m ² /day]	Relative humidity, RH [%]
Jan.	33	11.02	75.2
Feb.	33.68	12.55	78.1
Mar.	33.45	13.76	77.2
Apr.	32.86	15.94	77
May	31.93	11.3	70.4
Jun.	30.53	12.31	69.5
Jul.	28.77	12.91	69.3
Aug.	28.89	12.19	71.2
Sep.	29.99	13.55	70.7
Oct.	31.28	14.56	74.6
Nov.	32.74	13.91	75.3
Dec.	32.66	12.46	76.1

Design Features of the Dryer

The solar dryer has the shape of a home cabinet with tilted transparent glass top. The angle of the slope of the dryer cover is 5° for the latitude of location [8]. The dryer is set on casters to make it mobile. It is provided with air inlet and outlet holes at the front and back, respectively. The outlet vent is at higher level. The vents have sliding covers which control air inflow and outflow. The movement of air through the vents, when the dryer is placed in the path of airflow, brings about a thermo siphon effect, which creates an updraft of solar heated air laden with moisture out of the drying chamber. The source of air is natural flow.

Solar Dryer Design Considerations

A solar dryer was design based on the procedure described by [9] for drying dates (a cabinet type) and procedure described by [10] for drying rough rice (natural convection a mixed-mode type). The size of the dryer was determined based on preliminary investigation. The sample average thickness is 3mm (coarse) as recommended by [11]. The following points were considered in the design of the direct natural convection solar dryer system

- The amount of moisture to be removed from a given quantity of wet *tapioca*.
- The daily sunshine hours for the selection of the total drying time.
- The quantity of air needed for drying.

- Daily solar radiation to determine energy received by the dryer per day.
- Wind speed for the calculation of air vent dimensions.

Design Procedure

The size of the dryer was determined as a function of the drying area needed per kilogram of pulp of fruit. The drying temperature was established as a function of the maximum limit of temperature the fruit might support. From the climatic data of Table 1 the mean average day temperature is 32°C and relative humidity is 74 %. From the spreadsheet add-in for psychrometric data [12] the humidity ratio is 0.022 kg_{wv}/kg_{da}. The optimal drying temperature of cassava products was found to be 52°C [13] and final moisture content of *tapioca* for storage is 10 % wet basis.

Design Calculations

To carry out design calculations and size of the dryer, the design conditions applicable to Warri are required. The conditions and assumptions summarized in Table 2 are used for the design of the *Tapioca* dryer. From the conditions, assumptions and relationships, the values of the design parameters were calculated.

Table 2. Design Specification and Assumption

S/No	Items	Condition and assumption
1	Location	Warri (lan. 5°30' and long. 5°41')
2	Material	<i>Tapioca</i>
3	Drying period	All year round
4	Loading rate, m_p [kg/days]	100
5	Initial moisture content, M_i [%] w.b	79
6	Final moisture content, M_f [%] w.b	5
7	Ambient air temperature, t_{am} [°C]	32
8	Ambient relative humidity, RH_{am} [-],	0.74
9	Maximum allowable temperature, t_{max} [°C]	52
10	Drying time (sunshine hours) t_d [hrs]	10
11	Incident solar radiation, I_h [MJ/m ² /day]	13
12	Wind speed, w_s [m/s]	2.6
13	Collector efficiency, η [%]	20
14	Thickness of material, th_m [mm]	3 (rough)
15	Vertical distance between two adjacent trays, d [cm]	15

The amount of moisture to be removed from the product, m_w [kg] was calculated using the following equation:

$$m_w = m_p(M_i - M_f)/(100 - M_f) \quad (1)$$

where m_p [kg] is the initial mass of product to be dried; M_i [%] and M_f [%] wet basis are the initial moisture content and the final moisture content, respectively.

Final relative humidity or equilibrium relative humidity, ERH [%], was calculated using sorption isotherms equation given by [14] as follows

$$a_w = 1 - \exp[-\exp(0.914 + 0.5639 \ln M)] \quad (2a)$$

$$M = M_f/(100 - M_f) \quad (2b)$$

$$ERH = 100a_w \quad (3)$$

where a_w [-] is the water activity; M [kg_w/kg_s] dry basis.

The quantity of heat required to evaporate the water would be

$$Q = m_w h_{fg} \quad (4)$$

where Q [kJ] is the amount of energy required for the drying process and h_{fg} [kJ/kg_{wv}] the latent heat of evaporation. The amount needed is a function of temperature and moisture content of the crop. The latent heat of vaporization was calculated using equation given by [15] as follows

$$h_{fg} = 4186(597 - 0.56t_{pr}) \quad (5)$$

where t_{pr} [°C] is the product temperature

Moreover, the total heat energy, E [kJ] required to evaporate water was calculated as follows

$$E = \dot{m}_a (h_f - h_i) \tau_d / 3600 \quad (6)$$

where $\dot{m}$ [kg/s] is the mass flow rate of air; h_f [kJ/kg_{da}] and h_i [kJ/kg_{da}] are the final and initial enthalpy of drying and ambient air, respectively; τ_d [s] is the drying time.

The enthalpy, h [kJ/kg_{da}] of moist air at temperature t_d [°C] can be approximated as [16].

$$h = 1.007t_d + \omega[251.2131 + 1.5524t_d] \quad (7)$$

Average drying rate, d_r [kg/s], was determined from the mass of moisture to be removed by solar heat and drying time by the following equation

$$d_r = m_r / \tau_d \quad (8)$$

The mass of air needed for drying was calculated using equation given by [8] as follows

$$\dot{m}_a = \frac{d_r}{\omega_f - \omega_i} \quad (9)$$

where ω_f [kg_{wv}/kg_{da}] and ω_i [kg_{wv}/kg_{da}] are the final and initial humidity ratio, respectively. From the total useful heat energy required to evaporate moisture and the net radiation received by the tilted collector, the solar drying system collector area, A_c [m²], can be calculated from the following equation

$$A_c = E/I_h \tau_d \eta \quad (10)$$

where I [kJ/m²/s] is the total global radiation on the horizontal surface during the drying period η [%] is the collector efficiency and range from 30 to 50 % [8].

Volumetric airflow rate, $\dot{V}_a$ [m³/s] was obtained by

$$\dot{V}_a = \frac{\dot{m}_a}{\rho_a} \quad (11)$$

The air vent area, A_v [m²] can be calculated by

$$A_v = \dot{V}_a / w_s \quad (12)$$

where w_s [m/s] is the wind speed.

The length of air vent, L_v [m], will be equal to the length of the dryer. The width of the air vent, B_v [m], can be given by

$$B_v = A_v / L_v \quad (13)$$

The pressure difference across the tapioca bed will be solely due to the density difference between the hot air inside the dryer and the ambient air. Air pressure can be determined by equation given by [17] as

$$P = 0.00308 g (t_i - t_{am})H \quad (14)$$

where H [m] is the pressure head (height of the hot air column from the base of the dryer to the point of air discharge from the dryer) P [Pa] is the air pressure; g [m/s²] is the acceleration due gravity and t_{am} [°C] is the ambient temperature.

Results, Fabrication and Discussion

Table 3 shows the Microsoft (MS) excel spreadsheet computed results of the pertinent design parameters of the design. The prototype of the design with a minimum solar collector area of 1.08 m² was fabricated to be used in experimental drying tests.

Table 3. Pertinent Design Parameters

S/No	Parameter	Symbol	Units	Formula	Value
1	Initial humidity ratio	ω_i	kg _{wv} /kg _{da}	t_{am}, RH_{am}^*	0.02200
2	Initial enthalpy	h_i	kJ/kg _{da}	t_{am}, RH_{am}^*	87.50000
3	Equilibrium relative humidity	RH_f	%	$M_f, Eq. (2)$	51.00000
4	Final enthalpy	h_f	kJ/kg _{da}	ω_i, t_f^*	108.00000
5	Final humidity ratio	ω_f	kg _{wv} /kg _{da}	RH_f, h_f^*	0.02600
6	mass of water to be evaporated	m_w	kg	Eq. (1)	76.66667
7	average drying rate	d_r	kg _{wv} /hr	Eq (8)	3.83333
8	air flow rate	$\dot{m}_a$	kg/hr	Eq. (9)	958.33330
9	volumetric airflow rate	V_a	m ³ /hr	Eq. (11)	798.61110
10	Total useful energy	E	MJ	Eq. (6)	392.91670
11	Solar collector area	A_c	m ²	Eq. (12)	7.55609
13	vent area	A_v	m ²	Eq.(13)	0.08532
14	air pressure	P	Pa	Eq. (14)	0.90644
15	vent length	L_v	m	Spec.	6
16	vent width	B_v	m	Eq. (13)	0.01422
*read from spreadsheet add-in for psychrometric data (Oko and Diemuodeke, 2010)					

A solar dryer was designed and fabricated a prototype based on preliminary investigations of *Tapioca* drying under controlled conditions (laboratory dryer). The fabricated dryer will be used to dry *Tapioca* under controlled and protected conditions. The designed dryer with a collector area of 7.6 m² is expected to dry 100 kg of *Tapioca* from 79 % to 10 % wet basis in two days under ambient conditions all year round. The design computation was done using MS excel spreadsheet to facilitate lesser computational time and flexible design. A prototype of the dryer with 1.08 m² solar collector area was fabricated to be used in experimental drying tests.

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